MIRROR LAKE MONITORING: WATER LEVEL OBSERVATIONS AND GROUNDWATER-SURFACE WATER INTERACTIONS

Undergraduate Senior Research Thesis

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By

Kathleen M. Meiner

The Ohio State University

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Approved by

Audrey Sawyer, Advisor

School of Earth Sciences

TABLE OF CONTENTS

Abstract……………………………………………………………………..ii

Acknowledgements…………………………………………………………iii

List of Figures……………………………………………………………….iv

Introduction

Overview…………………………………………………………….1

Study Area………………………..……………………..…………………3

Methods

Hand Measurements…...……………………….…….…………….....……5

Sensor Data.……………………...…...……………………………..6

Analysis.……………………...…...……………………………………6

Water Level Time Series…………………...…..………………………7

Potentiometric Maps…………………………..…...……………………8

Three-Point Problems………………………………...……………………9

Discussion…………………………………………………………………11

Conclusions……………………………………………………………..13

Recommendations for Future Work……………………………….........……14

References Cited….……….………………………………………………15

Appendix…………………….………………………………………….16

Abstract

Groundwater-surface water interactions have great importance for clean and sustainable water use. To understand these interactions in an artificially constructed lake on the campus of Ohio State University, water level observations were made in Mirror Lake and ten piezometers surrounding the lake every month for a year. Measurements show that the lake recharges the surrounding aquifer throughout the year. The annual draining of the lake during the Ohio State-Michigan game leads to a lowering of water levels in surrounding piezometers. An area of low groundwater head also persists throughout the year between Mirror Lake and Neil Avenue that may indicate groundwater discharge to a storm drain that runs under Neil Avenue. Continued long-term measurements will be useful for understanding lake and groundwater budgets and can help support decisions about lake management, landscape design, and water use on campus.

ACKNOWLEDGEMENTS

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List of Figures

1. Styles of lake-groundwater interaction in a natural lake system (Winter et al., 1998).
2. Map of The Ohio State University Campus and Mirror Lake.
3. Shallow stratigraphy near Mirror Lake.
4. Map of Mirror Lake and measurement locations.
5. Photographs of surface water measurement locations.
6. Time series of daily rain and hydraulic heads.
7. Potentiometric maps of Mirror Lake and surrounding area.
8. Three-point diagrams for select piezometers in the winter and spring.
9. Photograph of gate to storm drain on the west side of Mirror Lake.
10. Conceptual model of water fluxes associated with Mirror Lake.

Introduction

Overview

Surface water and groundwater traditionally have been considered separate resources; however, they interact as one connected system that must be fully considered when managing water resources (Winter et al., 1998). Lakes can gain water through groundwater discharge, or the inflow of groundwater, across the entire lakebed or a portion of it (Figure 1A,C). Lakes can lose water through aquifer recharge, or seepage loss, across either the entire lakebed or a portion of it (Winter et al., 1998) (Figure 1B,C). Because this exchange of water carries dissolved chemicals, lake-groundwater exchange can influence the supply of carbon, nutrients such as nitrogen and phosphorus, and contaminants from aquifers to lakes and vice versa (LaBaugh et al., 2018). This can lead to changes in the biological and chemical characteristics in the lake system as groundwater flow paths evolve under the influence of climate change and human water use.

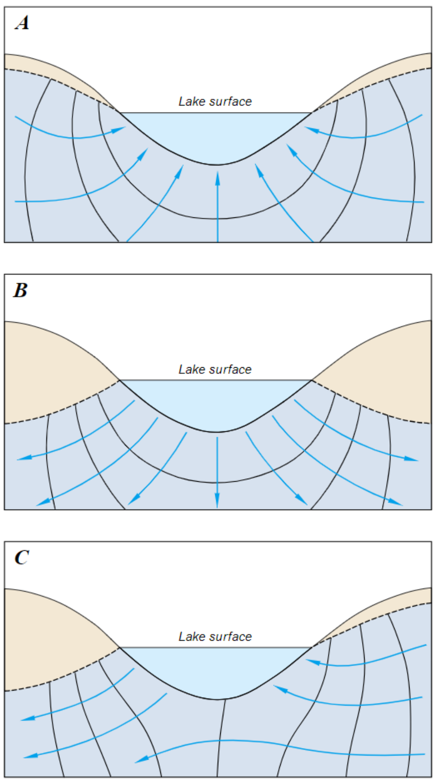

Figure 1: Lakes can receive groundwater inflow (A), lose water to the surrounding aquifer (B), or both (C) (Winter et al., 1998).

Much of what we know about lake-aquifer interactions comes from studying fairly natural systems. For example, a study of long-term changes in the Prairie Pothole Region wetlands of the United States found that groundwater flow was responsible for the largest source of solutes to the ponds, though it represented the smallest source of water. The ponds were also observed to lose water to groundwater recharge in drier years (LaBaugh et al., 2018). In Canada's Boreal Plains, shallow groundwater fluxes to and from pond-peatlands were controlled by water storage in the adjacent riparian peatlands and contributed to as much as 23% of inputs and outputs. Groundwater also influenced pond permanence and chemistry (Ferone et al., 2004). In much larger lakes such as Lake Erie, field measurements have shown that groundwater discharge contributes to nutrient loading near the shoreline (Knights et al., 2017). These studies are only a small portion of the many on lake-groundwater interactions in natural lakes.

Yet many lakes are either manmade or highly altered and enhanced. In a US EPA survey of 111,119 lakes, 48% were manmade (USEPA, 2016). Smaller manmade lakes and ponds often occur in densely populated settings where humans influence both the surface water and groundwater systems. One way that humans influence hydrology is through infrastructure such as stormwater and drinking water networks, which act as “urban karst,” creating preferential underground flow paths to lakes and streams. This subsurface infrastructure increases the flow of water, organic matter, energy, and nutrients compared to more natural watersheds (Kaushal and Belt, 2012). Urban runoff and leaky wastewater systems recharge aquifers, introducing a cocktail of anthropogenic contaminants to groundwater. As an example, chemical analyses of the Hockanum River aquifer in Manchester, Connecticut found that urban regions contained higher levels of sodium and nitrogen, thought to be from de-icing road salt, leaky sewers, and fertilizer application (Mullaney et al, 1997). Given the complexities in urban hydrology and their impacts on water chemistry, it is essential to examine lake-aquifer connections in urban settings. In this study, I monitored groundwater levels over a year near Mirror Lake on The Ohio State University’s main campus in Columbus, Ohio (USA) to understand the complex interactions of the managed lake system with the surrounding aquifer. I show that this artificially enhanced lake loses water to the aquifer year-round. Much of the lost lake water appears to flow towards a storm drain located under Neil Avenue, demonstrating the strong connections between surface water, groundwater, and urban infrastructure on campus.

Study Area

Mirror Lake is a highly managed, artificially augmented urban lake on The Ohio State University's main campus in Columbus, Ohio (Figure 1). The site lies within the Mouth Olentangy River watershed (HUC (050600011103) and receives an annual average precipitation of 109 cm, according to the National Weather Service.

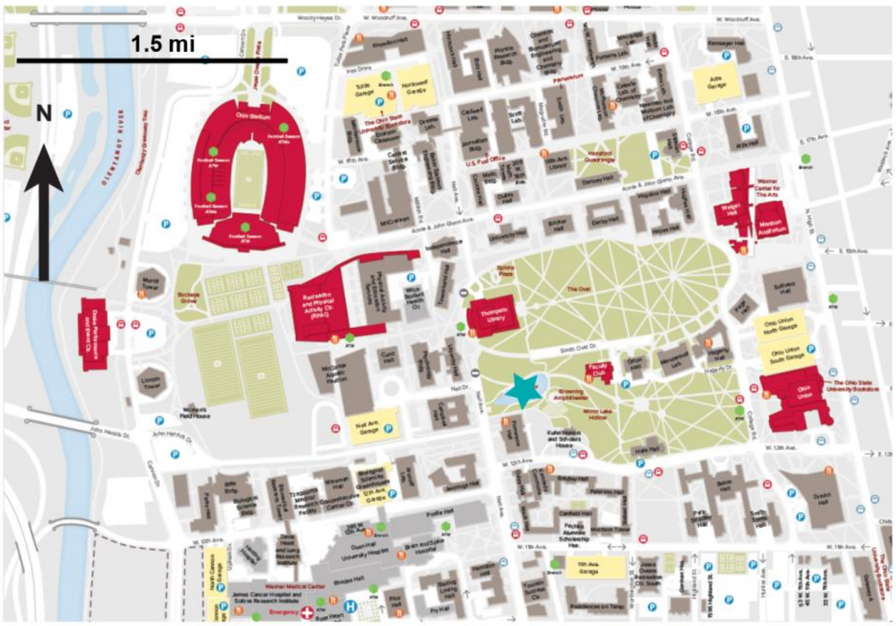

Figure 2: Map of Ohio State's campus, modified from Ohio State's library website (2019). Location of Mirror Lake is denoted by a blue star.

The shallow soils and sediments beneath Mirror Lake consist mainly of artificial fill and vary in thickness from 1-3 m (Figure 3). Beneath this fill is 0.5-9.0 m of unconsolidated sands, gravels, and silts of fluvial and glacial origin (Madson, 2019) (Figure 3). These unconsolidated sediments are underlain by 18.9 m of relatively impermeable shale associated with the Olentangy and Ohio Shale Formations and the Delaware Formation (McMillan, 1999). Beneath this shale is the Devonian-age Columbus Limestone, which includes a system of caverns underneath the South Oval through which groundwater travels (McMillan, 1999).

The lake is surrounded by a network of ten piezometers that were installed in July 2019 with a Geoprobe (Figure 4). All piezometers have 2-inch PVC casing and are screened through the water table to various depths ranging from 4.2 to 9.1 m. In addition to this piezometer network, a sensor is installed in Mirror Lake to continuously monitor the surface water level, temperature, and electrical conductivity (In-Situ Aqua Troll 200). Another sensor is also installed in a deep monitoring well that is completed within the confined limestone aquifer (Figure 3). The well has 6" casing from the ground to the bottom of the shale aquitard (21.6 m depth) and is open from 21.6 m to the bottom at 36 m. Both sensors were installed in October of 2018 and record measurements every 15 minutes. The sensors are attached to an In-Situ Cube-300 telemetry system, which transmits readings to the web (https://mirrorlake.byrd.osu.edu/). Cables running from the sensors to the telemetry system are protected in conduit and fully trenched.

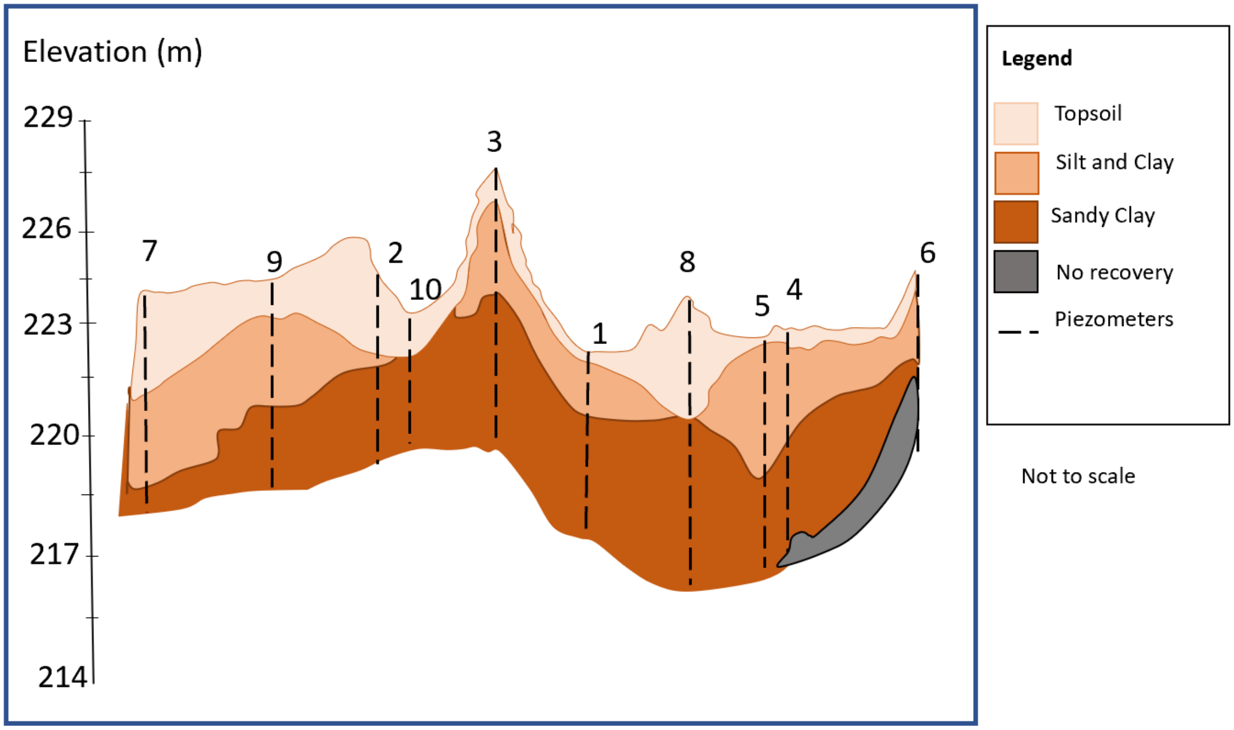

Figure 3: Cross-section of shallow stratigraphy near Mirror Lake, courtesy of Mazvita Chikomo.

METHODS

Hand-Measurements

Depth to water was measured approximately every month from July 2020 to July 2021 in all accessible piezometers (Figure 4). To make a measurement, piezometer caps were opened with a 14 mm socket wrench, the beep tape was lowered, and depth to water was measured from the top of the PVC casing. Changes in lake level were also assessed by measuring the distance from the lake surface to two fixed reference points located at the eastern weir and the stone patio of the overlook (Figure 5). Approximate error for all water level measurements is 0.5 cm.
Relative elevations of the tops of casing and lake reference points were surveyed with a Total Station. These elevations were used to calculate hydraulic head from depth to water measurements.

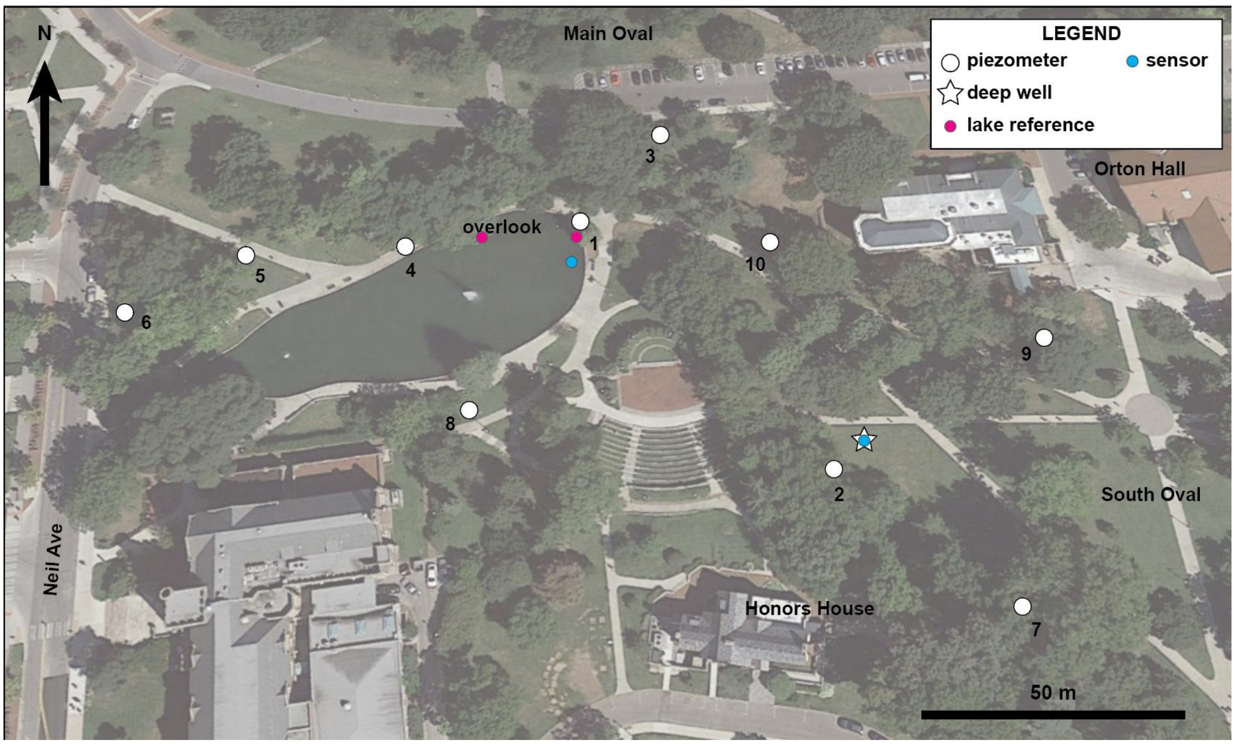

Figure 4: Aerial photograph of Mirror Lake (Google Earth, 2019) showing locations of piezometers, lake reference points for lake level measurements, and sensors.

Figure 5: Photographs of the stone patio overlook (left) and eastern weir (right) where lake levels were measured from fixed reference points (indicated with arrows).

Sensor Data

Water level, temperature, and conductivity sensors in the deep monitoring well and lake were replaced in the summer of 2021 and fall of 2021, respectively, due to battery failure. The record of water depth from Mirror Lake was converted to hydraulic head by comparing manual monthly measurements to determine the elevation of the sensor. The sensor elevation was then used to convert continuous water depths to lake surface levels (or hydraulic head). Unfortunately, the sensor only logged less than two months of reliable data before readings became unreliable due to dwindling battery power. The loss of fidelity began around September 19, 2020, and logging apparently ceased in November of 2020. Therefore, sensor data were only used to estimate the date when Mirror Lake was drained for the Ohio State-Michigan football game and the change in water level. It is important to note that no direct hand measurements could be made during this period, so the change in water level could not be vetted and may be inaccurate.

Daily rain and air temperature data were recorded at a weather station on the Main Campus (40˚00'13.34" N,83˚02'19.54" W) every 5 minutes (courtesy of Byrd Polar & Climate Research Center).

Analysis

Hydraulic head values in the lake and piezometer network were used to hand-contour the water table in the vicinity of Mirror Lake. The lake shoreline was inferred to be a line of constant head.

Changes in flow direction were estimated for two areas of interest in the northwest corner of Mirror Lake and South Oval using the "three-point problem" method across winter 2020 and spring 2021. The approach assumes that hydraulic head varies linearly between the chosen piezometers (4, 5, 6 and 2, 8, 10 in Figure 4).

RESULTS

Water Level Time Series

Over the study year, the lake level remained higher than the levels of all other piezometers (Figure 5). Piezometers with the lowest water levels were piezometers 5 and 6 in the Northwest corner of the study area (Figures 4 and 6). The total difference in hydraulic head from piezometer 6 to the lake was approximately 4.0 m (218.2 m to 222.2 m) over a distance of about 25 m.

Lake water levels varied by only a few centimeters on the dates when hand measurements were possible (222.60 to 222.70 m). Recorded levels were generally around 222.65 m. However, the lake was inaccessible for measurement from the time when it was drained for the Ohio State-Michigan game until it was refilled, so recorded lake levels do not reflect the full range of variability. Sensor data suggest that the lake was drained on approximately November 11, 2020, and the level dropped by 85 cm in a little over an hour (Appendix D). No sensor data were recorded on the day when the lake was refilled. The water levels of the piezometers varied less than the inferred lake level variation (85 cm). Water levels at piezometers 1, 2, and 9 were most stable, (ranges of 16, 10, and 14 cm over the year respectively). Water levels at piezometers 4, 5, and 6 were the most dynamic, showing a variation of 55, 71, and 44 cm over the year respectively. The water levels of the piezometers varied less than the inferred lake level variation (85 cm). Water levels at piezometers 2, 1, and 9 were most stable, (ranges of 10, 16, and 14 cm over the year respectively). Water levels at piezometers 4, 5, and 6 were the most dynamic, showing a variation of 55, 71, and 44 cm over the year respectively.

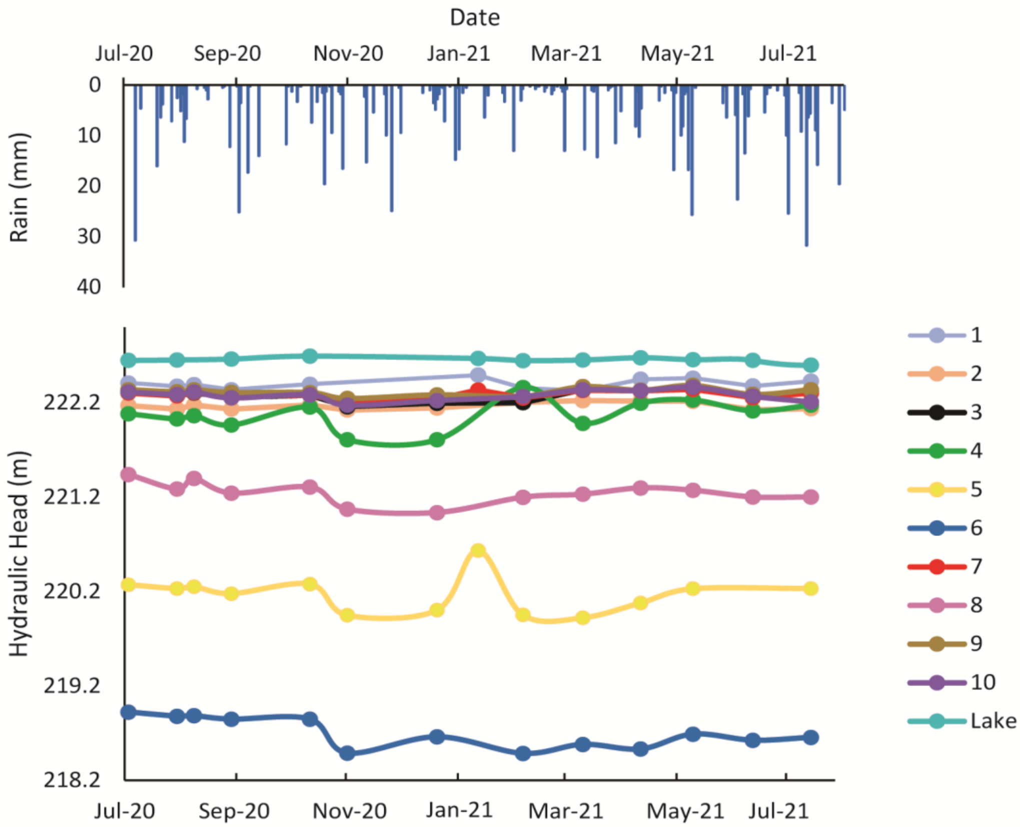

Figure 6: Daily rain (above) and water levels (below) of Mirror Lake over the year 2020-2021. Hydraulic head remains relatively constant across the year, with piezometers 4 and 5 being the most dynamic. Lake levels are stable over the period of record, but sensor data (not shown) suggest that the lake level declined by ~85 cm on November 10 when the lake was drained for the Ohio State-Michigan game.

Potentiometric Maps

Potentiometric maps (Figure 7) show that flow generally moves from a region of high hydraulic head at the lake to regions of lower hydraulic head towards the North and South. In other words, the lake is losing water to the unconfined aquifer during all seasons. The lowest values of hydraulic head are observed to the Northwest at piezometer 6 near Neil Avenue, and the hydraulic gradient is steepest there. The groundwater mound beneath the lake appears to extend eastward along the South Oval. This water table mound is somewhat opposite of the local topography—areas of higher elevation have slightly lower hydraulic heads year-round.

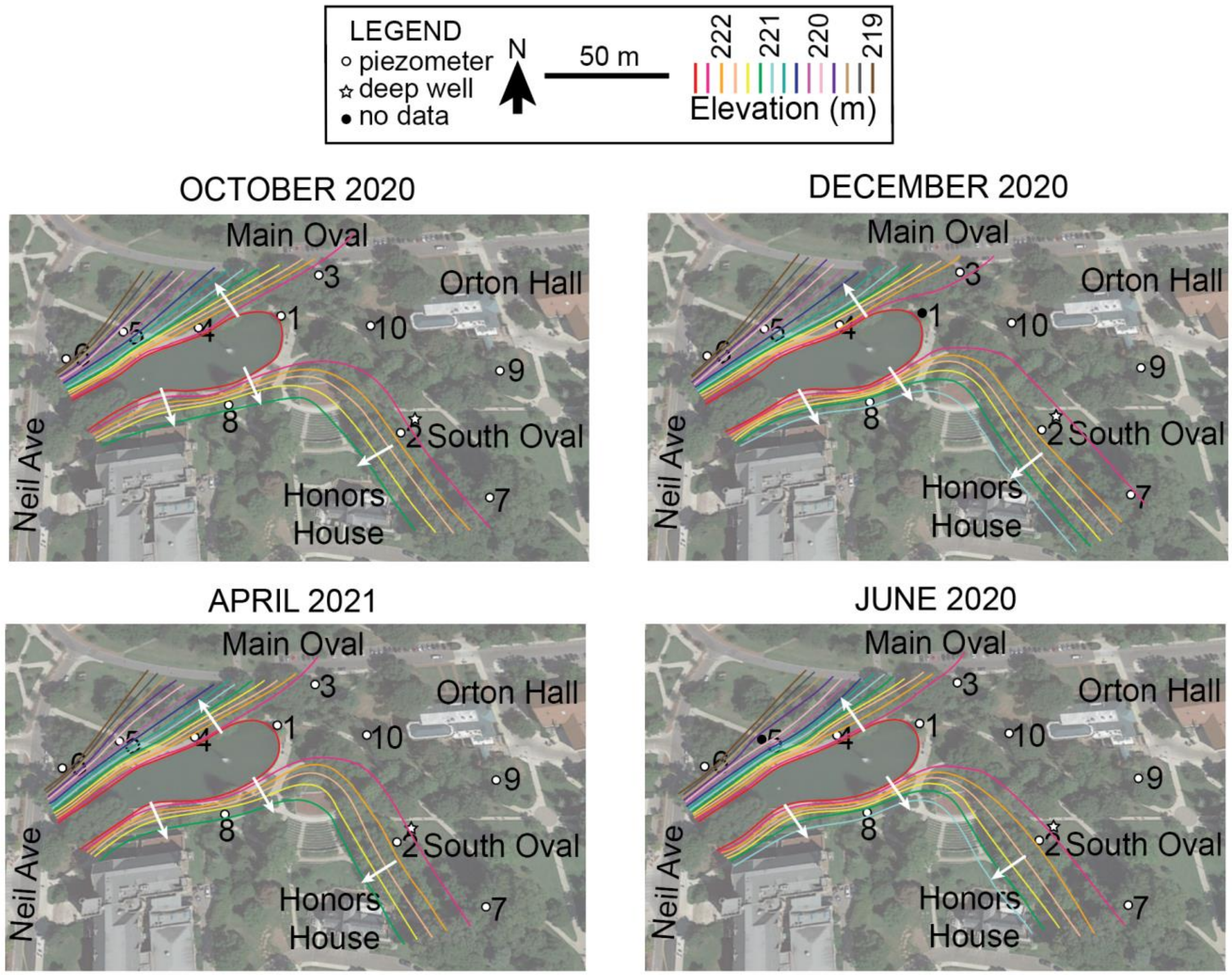

Figure 7: Potentiometric maps of Mirror Lake and surrounding area across four seasons. White arrows indicate flow direction.

Three-Point Problems

Three-point diagrams show minor to negligible variation in flow direction across seasons (Figure 7). Flow directions in the area of steepest hydraulic gradient (Piezometers 4, 5, and 6) are relatively consistent throughout the year. Although water level rose by 40 cm at piezometer 4 between December and April, the observed flow direction only shifted northward by 2 degrees. Piezometers 2, 8, and 10 exhibited even less of a change in flow direction. Water level rose 7-25 cm in the spring, and flow direction was consistent to the Southwest.

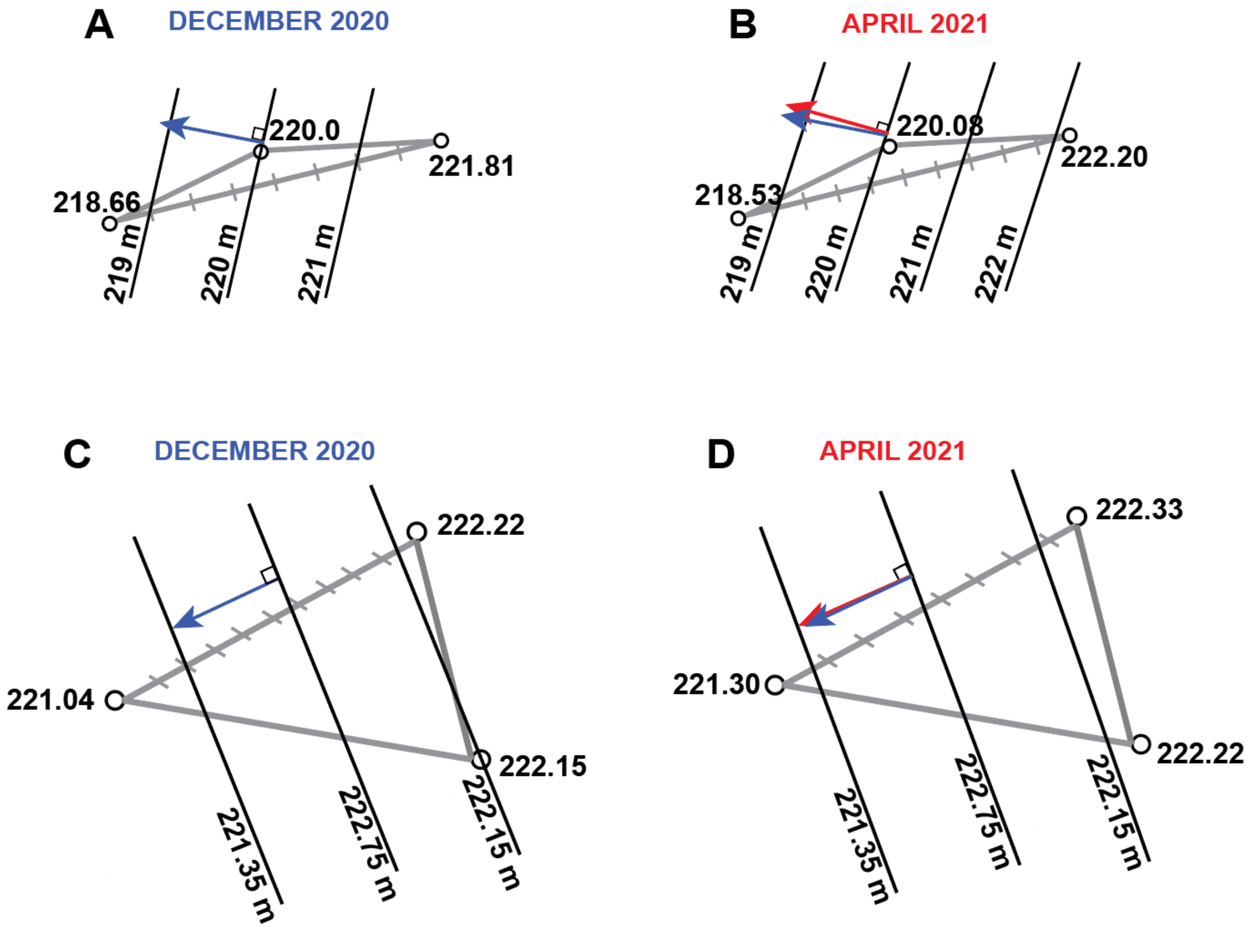

Figure 8: Three-point diagrams for two areas of interest and two seasons: Piezometers 4, 5, and 6 during winter 2020 (A) and spring 2021 (B), and Piezometers 2, 8, and 10 during winter 2020 (C) and spring 2021 (D). Flow directions in winter are shown with blue arrows, while flow directions in spring are shown in red.

Discussion

The Ohio State University's effort to enhance a natural spring on its campus resulted in the creation of a losing lake. Its source water is pumped from Columbus' municipal water supply in the Mouth Olentangy River watershed. This municipal water source may come under tighter conservation under population growth and climate change in the future. If so, it may become undesirable to use drinking water to augment a losing lake. Water has traditionally been deemed plentiful in the Midwest, but many lakes have experienced declining water levels in recent decades, mainly due to groundwater extraction and climate change, though the most prominent and severe example is seen in Lake Michigan and Lake Superior (Egan, 2017). This loss in Lake Michigan and Superior has been exacerbated by withdrawal and threats of increased withdrawal of water for uses outside of the Great Lakes watershed with limited returns.

At Mirror Lake, the inferred ground flow northwest towards Neil Avenue is consistent with discharge to an area of lower elevation, possibly a storm drainage network. A campus map of subsurface infrastructure confirms that a storm drain indeed runs underneath Neil Avenue (personal communication, Ruth Miller). A portion of the storm drain is visible on the western side of Mirror Lake (Figure 9). Stormwater systems often receive groundwater discharge, as they are designed to divert water out of cities, while public drinking water networks often lose water to the surrounding aquifer, as they are pressurized to deliver water to users (Kaushal and Belt, 2012). Together, this integrated network of water pipes forms the urban karst system in heavily developed regions like The Ohio State University campus. When pipes are laid, the ground is trenched, and the trenches are backfilled. These backfill materials also influence groundwater exchange with storm drainage networks and can create additional hydrologic flow paths within the urban karst structure.

Figure 9: Photograph of a gate connected to the storm drain on the west side of Mirror Lake.

Mirror Lake may be a fairly extreme example of human-modified flow paths in an urban watershed. I infer that from start to finish: surface water is withdrawn from the Scioto River and treated for municipal drinking water, discharged to augment Mirror Lake where it recharges the surrounding aquifer, discharges to the Neil Avenue storm drain, and eventually flows to the Olentangy River (Figure 10).

Urbanization in the campus area not only modifies recharge from Mirror Lake but likely also modifies groundwater recharge across the land surface. Irrigation may increase groundwater recharge in manicured lawn spaces, while paved surfaces may locally decrease recharge. The net effects on groundwater resources are uncertain. In a study of urban groundwater in Spanish Springs Valley, Nevada, infiltration of imported surface water for irrigation was the main source of groundwater recharge. Using groundwater models, the study suggested that as urban development and groundwater withdrawal increases, groundwater resources may dwindle (Berger et al., 1997). On our campus, we do not rely on groundwater as a drinking water source, but long-term groundwater levels could still influence surface water bodies, foundation stability, and other factors.

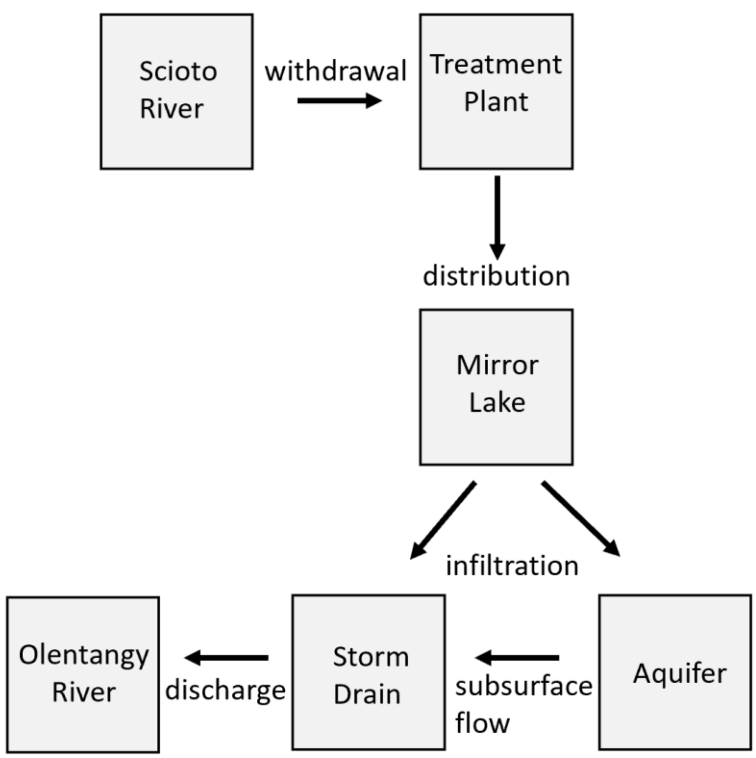

Figure 10: Flow diagram showing the proposed movement of water in Mirror Lake from origin in the Scioto River to its final destination as aquifer recharge or discharge to the Olentangy River.

Conclusions

The enhancement of a natural spring on campus has led to the creation of a losing lake. A year of monthly piezometer measurements show that lake levels in Mirror Lake remained consistently higher than piezometer levels, indicating consistent loss of lake water to the surrounding aquifer. Piezometer levels varied by up to 66 cm throughout the year and were affected predominantly by the draining of Mirror Lake in November 2020 rather than rain events. Flow directions were fairly stable across the year, and the steepest gradient was found towards the northwest corner of the lake, indicating potentially rapid flow of groundwater towards a stormwater drainage system that is partially visible through the lake's west gate.

Together, these observations highlight the strong influence of humans on surface water-groundwater interactions in an urban setting. A better understanding of how these systems interact is important for water management and conservation. For example, the lake is fed by municipal drinking water from the city of Columbus and loses water to the surrounding aquifer, which then appears to discharge to the storm drain. If the demand for Columbus' drinking water increases, the use of the water to maintain Mirror Lake may become less desirable.

Recommendations for Future Work

To further understand interactions between surface water and groundwater in a heavily urbanized artificial lake system, this study could be extended for longer periods of time. Measurements from hydrogeology or geophysics classes could augment long-term observational datasets. For example, hydrogeology classes could measure changes in flow direction across multiple years, including dry and wet years. They could also observe recharge episodes during short hydrologic events like rain and snow. Before and after the Ohio State-Michigan game, they could make high-resolution measurements of changes in water table depth when the lake is drained and refilled. Additional In-Situ Aqua Troll 200 sensors could be placed in piezometers to help monitor rapid water level fluctuations. Geophysics classes could also conduct refraction surveys to identify the depth and velocity of relatively flat geologic layers. Results from refraction surveys have not yet been processed to determine layers of interest.

Currently, a groundwater model is being developed to understand more about water table fluctuations near the lake and estimate losses of surface water to the surrounding aquifer. One of the greatest challenges in model development is uncertainty about the subsurface, including both the geologic structure and manmade infrastructure such as storm drains and irrigation systems. Maps of subsurface infrastructure could be combined with field observations and models to improve our understanding of groundwater flow in this heavily urbanized setting. Models have been successful at predicting changes in groundwater levels under urbanization in Spanish Spring Valley, Nevada (Berger et al., 1997).

Furthermore, additional piezometers could be established around Mirror Lake in data poor areas to collect more hydraulic head readings across a larger area. This would allow for more accurate potentiometric maps and groundwater modeling. Additionally, seepage meters could be deployed in the lakebed in an effort to directly quantify rates of water loss to the underlying aquifer, though the efficiency of measurements may vary with permeability in the relatively impermeable Mirror Lake bed (Rosenberry et al., 2020). It is possible that rates of infiltration into the lakebed vary spatially and temporally. In fact, a spring is activated on the north side of the lake when the lake is drained for Michigan Week. This natural feature would be interesting to study with seepage meters over seasons. The measurements could also be used to aid in model development and validation.

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Appendix

Appendix A: Table of piezometer data. Geologic descriptions are from drilling notes in 2019.

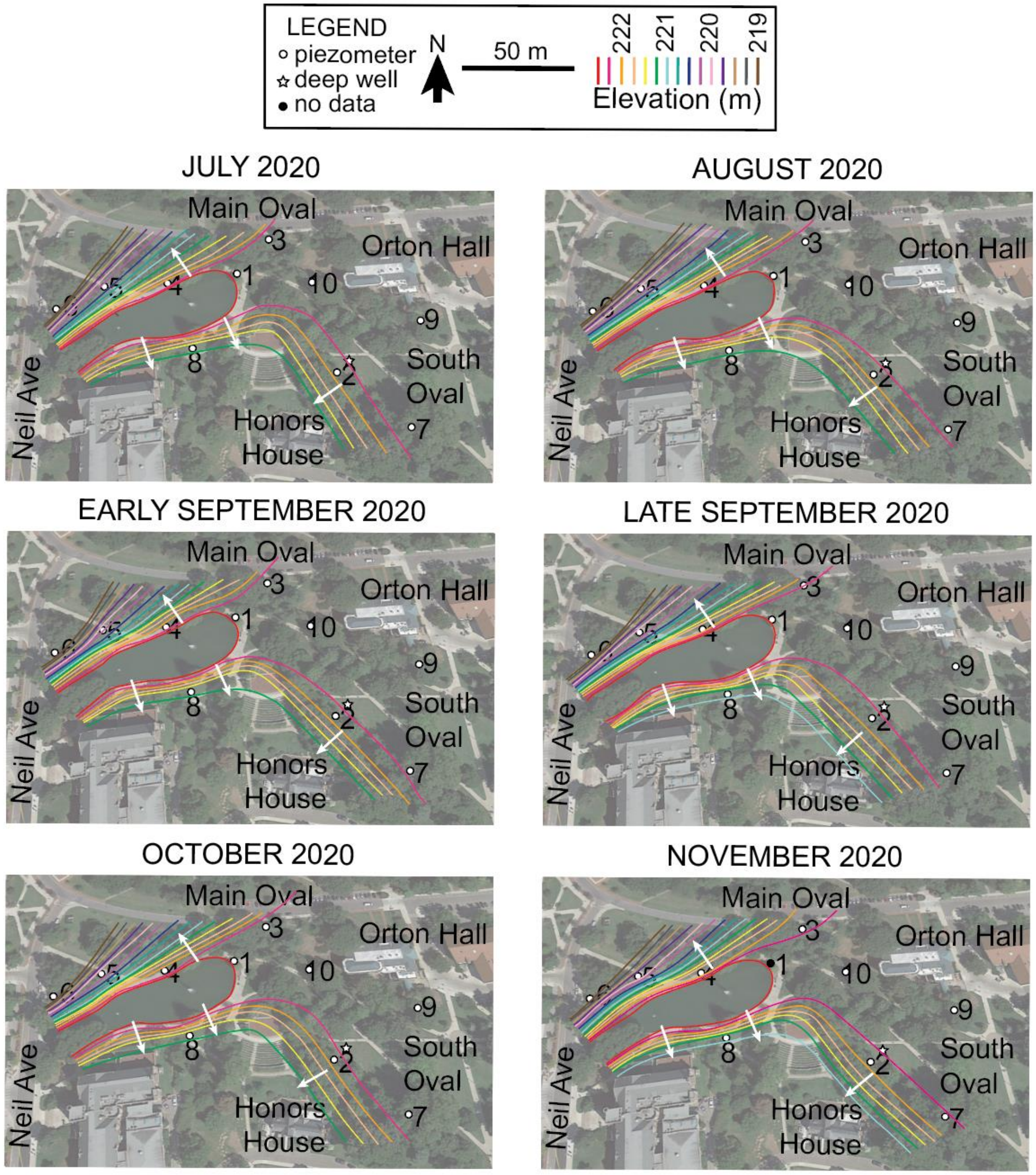
Piezometer	Latitude (deg)	Longitude (deg)	Depth Drilled (ft)	Sample Description	Top of Screen Depth (ft)	Bottom of Screen Depth (ft)	Elevation (ft)
1	39.9982	-83.0137	15	0-1.5 ft of topsoil, 1.5-8 ft of silty to sandy clay, 8-14 ft of weakly interbedded clayey sand and sandy clayey gravel, and 13-15 ft of pea gravel with sand and clay	4.8	14.8	223.338
2	39.9976	-83.0131	15	0-6.3 ft of topsoil, and 6.3-15 ft of clayey sand with gravel and clayey gravel with sand	4.4	14.4	223.546
3	39.9984	-83.0134	25	0-3 ft of topsoil, 3-10 ft of silty clay weakly interbedded with clayey sand, and 10-25 ft of sand and clayey gravel	14.8	24.8	226.444
4	39.9982	-83.0143	20	0-1.8 ft of top soil, 1.8-6.5 ft of silty to sandy clay and trace gravel, 6.5-17 ft of silty to clayey gravel, 17-17.5 ft of clay, and no recovery from 17.5-20 ft	6.4	16.4	223.374
5	39.9981	-83.0147	25	0-0.5 ft of topsoil, 0.5-10.9 ft of silty to sandy clay and trace gravel, 10.9-15.6 ft of silty gravel and silty sand, 15.6-16.0 ft of clay, and 16-25 ft of silty sand with decreasing silt content down section	14.8	24.8	224.103
6	39.9980	-83.0151	30	0-0.9 ft of topsoil, 0.9-7.5 ft of silty to sandy clay and trace gravel, 7.5-7.8 ft of gravel with some clasts of asphalt, 7.8-15 ft of no recovery, 15-22.4 ft of very silty sand with some gravel towards the top, and 22.4-30 ft of weakly	19.8	29.8	224.795

				interbedded silty gravel with sand and silty sand with gravel			
7	39.9974	-83.0127	18	0-9 ft of topsoil and sandy to silty clay with trace gravel, 9-14 ft of finely laminated silty clay, 14-18 ft of medium sand with gravel, and 18-18.5 ft of gravelly sand with clay and sandy gravel	7.8	17.8	223.483
8	39.9978	-83.0141	25	0-11 ft of top soil and silty-sandy clay with trace gravel, 11-15.3 ft of clayey and very fine sand, 15.3-16.5 ft of sandy clay, and 16.5-25 ft of clayey sand and gravel	14.8	24.8	224.562
9	39.9980	-83.0125	20	0-4.3 ft of topsoil and clay, 4.3-12.2 ft of silty clay with trace gravel, of 12.2-20 ft of silty gravels and sands	8.6	18.6	225.169
10	39.9981	-83.0131	14	0-5.5 ft topsoil and clay with trace gravel, 5.5-12.5 clayey gravel, and 12.5-14 ft of silty sand with gravel	3.8	13.8	223.679

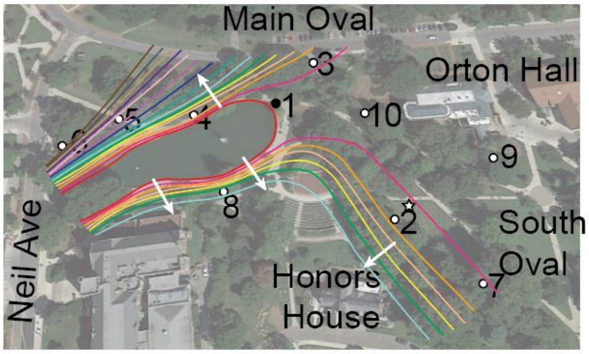
Appendix B: Measured depths to water on 13 dates. All depths are relative to coordinates shown. For piezometers, coordinates refer to the top of casing. Lake reference points are indicated in Figure 4 (Lake 1 is the top of the center stone paver on the left photograph, and Lake 2 is the top of the corner of the weir on the right photograph). "n.d." indicates no data due to inaccessibility (snow, etc).

Piezometer	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*Lake 1*	*Lake 2*
Northing (m)	4429505.78	4429438.68	4429531.07	4429499	4429496.6	4429481.82	4429407.76	4429454.67	4429470.03	4429498.26	4429504.85	4429494.9
Easting (m)	328093.03	328147.91	328114.27	328051	328012.32	327986.5	328182.03	328067.67	328200.88	328139.9	328074.88	328092.35
Elevation (m)	223.338	223.546	226.444	223.374	224.103	224.795	223.483	224.562	225.169	223.679	223.629	223.059
7/30/20	0.928	1.375	4.132	1.29	3.83	5.872	1.18	3.122	2.83	1.365	0.98	0.405
8/25/20	0.963	1.412	4.172	1.345	3.871	5.915	1.211	3.277	2.852	1.393	0.975	0.397
9/3/20	0.945	1.37	4.14	1.31	3.85	5.91	1.175	3.165	2.83	1.365	n.d	0.415
9/23/20	1	1.412	4.189	1.41	3.924	5.947	1.218	3.319	2.86	1.427	0.965	0.385
11/4/20	0.941	1.371	4.162	1.221	3.823	5.946	1.201	3.255	2.861	1.394	0.934	n.d
11/24/20	n.d	1.423	4.285	1.565	4.153	6.305	1.286	3.489	2.924	1.505	n.d	n.d
1/11/21	n.d	1.4	4.248	1.566	4.099	6.134	1.244	3.525	2.885	1.455	n.d	n.d
2/2/21	0.845	n.d	n.d	n.d	3.468	n.d	1.147	n.d	n.d	n.d	0.959	0.105
2/26/21	0.981	1.341	4.243	1.013	4.151	6.309	1.232	3.363	2.901	1.413	0.981	0.382
3/30/21	1.011	1.322	4.105	1.391	4.181	6.214	1.152	3.331	2.798	1.341	0.975	0.481
4/30/21	0.89	1.328	4.115	1.177	4.023	6.263	1.158	3.264	2.835	1.35	0.951	0.305
5/28/21	0.877	1.33	4.086	1.145	3.873	6.105	1.141	3.289	2.785	1.315	0.972	0.445
6/29/21	0.96	1.42	4.17	1.26	n.d	6.17	1.23	3.36	2.88	1.41	0.98	0.425
7/30/21	0.91	1.41	4.13	1.2	3.87	6.14	1.18	3.36	2.83	1.47	1.3	0.46

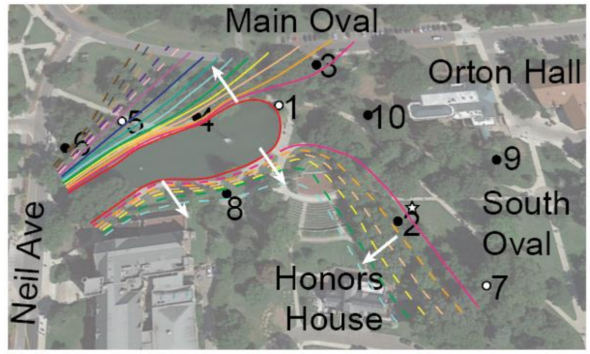
Appendix C: Potentiometric maps of Mirror Lake and surrounding area across the data measurement period from July 2020 to July 2021. White arrows indicate flow direction.



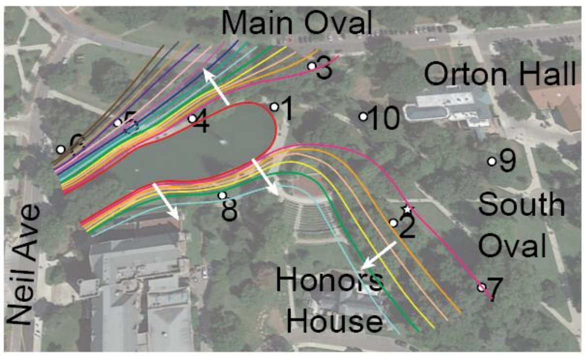
DECEMBER 2020



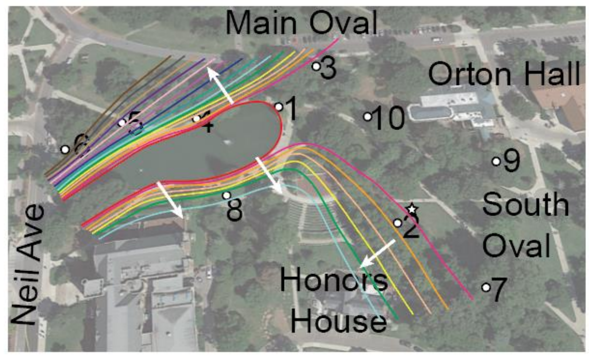
JANUARY 2021



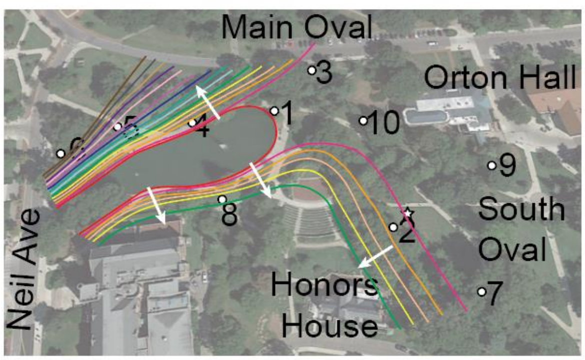
FEBRUARY 2021



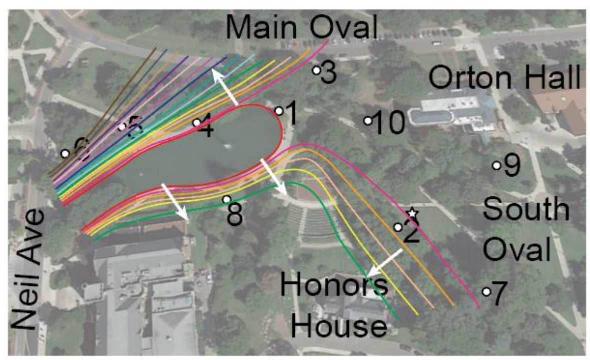
MARCH 2021



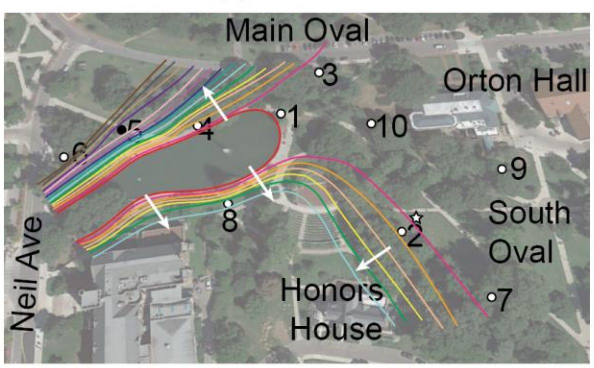
APRIL 2021



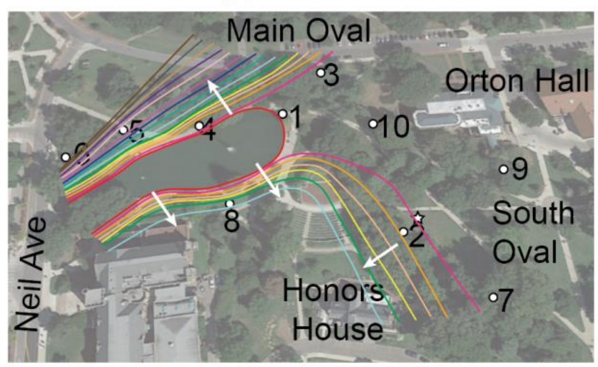
MAY 2021



JUNE 2020



JULY 2021



Appendix D: Recorded water levels showing sensor data and hand measurements. Sensor data became unreliable due to battery failure in September 2020, and logging ceased in November 2020.